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Sampling frequency evaluation procedures presented utilize a number of simplifying assumptions and basic statistical methods. Employing such an approach will facilitate use of these procedures and, therefore, set the stage for wider understanding and use of more sophisticated approaches that may be developed at a later date. Practical application has been an overriding consideration in development of these procedures.

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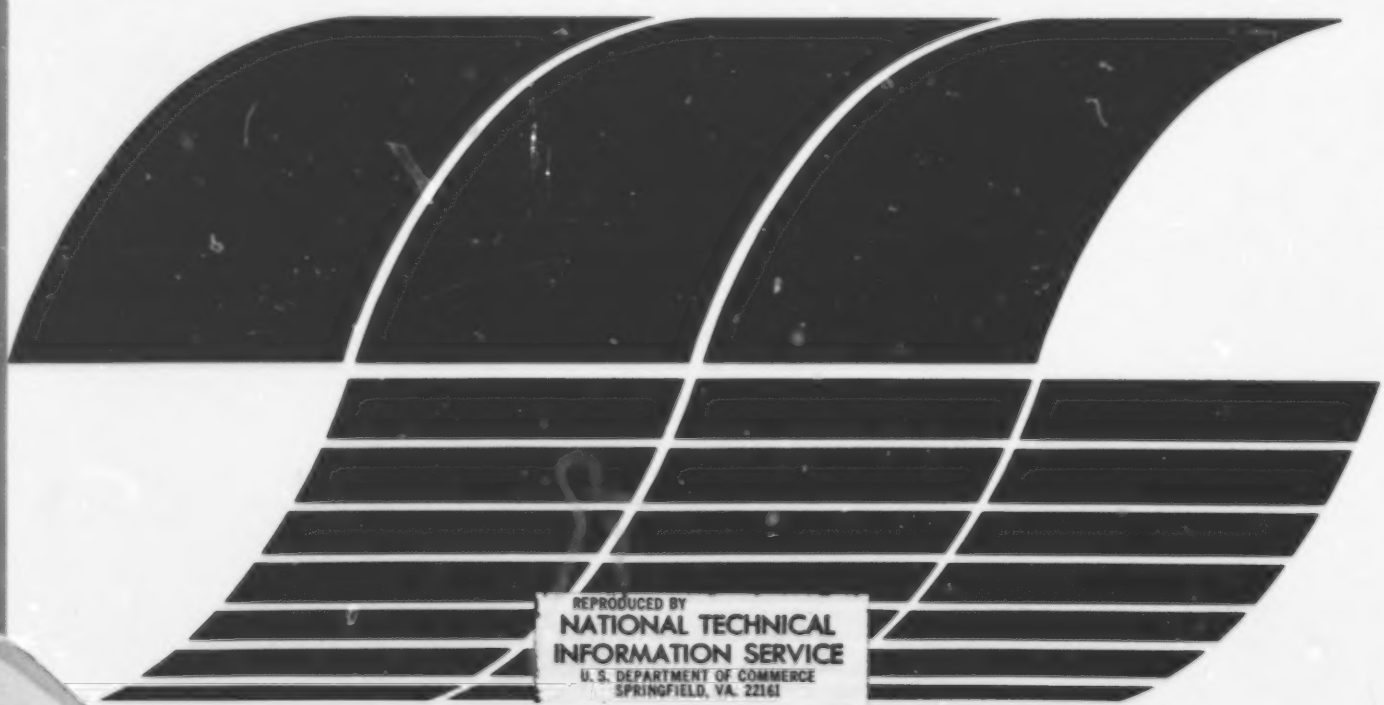

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by

Robert C. Ward
Agricultural and Chemical Engineering Department
Colorado State University

and

Knud Strange Nielsen
Data Analysis Section
Water Quality Institute
Horsholm, Denmark

Contract Number CB-6-99-2530-A

Project Officer
Donald B. Gilmore
Monitoring Systems Design and Analysis Staff
Monitoring Systems Research and Development Division
Environmental Monitoring and Support Laboratory
Las Vegas, Nevada 89114

U.S. ENVIRONMENTAL PROTECTION AGENCY
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ENVIRONMENTAL MONITORING AND SUPPORT LABORATORY
LAS VEGAS, NEVADA 89114

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FOREWORD

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach which transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory--Las Vegas contributes to the formation and enhancement of a sound monitoring data base for exposure assessment through programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment
- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs.

This report covers a procedure for evaluating sampling frequencies of established water quality monitoring networks. This report is intended to assist monitoring systems managers to more efficiently distribute resources between sampling sites and laboratory facilities in an effort to achieve better data at a lower cost. For further information contact the Monitoring Systems Research and Development Division at this Laboratory.

George B. Morgan
Director
Environmental Monitoring and Support Laboratory
Las Vegas

PREFACE

There is a large number of general water-quality management agencies in the United States that are functions of state and local governments. The agencies routinely manage water quality within political boundaries. To support such management, the agencies operate a wide variety of monitoring programs. One type of water-quality monitoring common to most agencies is a routine fixed-station network. The purpose of such networks has, in the past, often been poorly defined, especially from a statistical viewpoint. However, there currently are several efforts being made to clarify the goals of this type of monitoring. This, in turn, is resulting in the need to evaluate the design of the network, particularly the sampling frequencies.

The sampling frequency evaluation procedures presented in this report utilize a number of simplifying assumptions and basic statistical methods. Hopefully, employing such a straightforward, simple approach will facilitate use of the evaluation procedures and, therefore, set the stage for wider understanding and use of more sophisticated approaches that may be developed at a later date. Practical application has been an overriding consideration in development of the evaluation procedures.

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I. INTRODUCTION

During the past 10 years, a large number of water-quality monitoring programs have been established by local, state and federal water-quality management agencies in response to the Water Pollution Control Act of 1965 (PL 89-234), the Water Pollution Control Act Amendments of 1972 (PL 92-500) and the Safe Drinking Water Act of 1974 (PL 93-523).

The legal purpose of these monitoring efforts is, in general, simply to "monitor" water quality; however, the efficient operation of a monitoring program requires a detailed definition of "monitor." Since water-quality monitoring by definition is a statistical sampling operation, it is highly desirable that the monitoring purpose be carefully defined in terms of the statistical precision and confidence sought and the eventual use of the results.

In order to comply with the law's requirement to "monitor" water quality, most management agencies selected, on the basis of the experience of their personnel, sampling sites and relevant parameters to be measured. The sampling frequency was, in general, determined by the capacity of the laboratory and, in turn, the samples were equally divided among the stations.

Over the years, these monitoring systems have been revised and modified to reflect more specific monitoring objectives. A recent study by the Environmental Protection Agency's Standing Work Group on Water Monitoring (1977) points out that routine fixed-station monitoring determines trends in water quality while intensive surveys should be used to obtain enforcement information. The recommendations of the study emphasize the need to shift monitoring resources from routine fixed-station monitoring to intensive surveys.

To ensure that such shifts occur with a minimum impact on the trend-detection ability of the fixed-station network, there needs to be a careful statistical evaluation of a network's design. A complete and thorough theoretical statistical evaluation of an agency's monitoring network is often beyond the resources of an agency that is operating an active and aggressive regulatory monitoring program.* It is possible, however, for agencies to perform more basic statistical evaluations if such evaluations can take advantage of existing personnel, programs, facilities, data and

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*Dunnette, David. Personal communication, Dunnette of the Water Quality Division, Department of Environmental Quality, Portland, Oregon, to Robert C. Ward, August 24, 1977.

data handling procedures and if they do not require a large commitment of the agency's resources.

Evaluation of the design of a regulatory water-quality monitoring system, in general, involves examining: (1) sampling station locations, (2) parameter coverage, and (3) sampling frequencies (where, what and how often to sample). Evaluation of the first two design aspects requires the collection of additional data between existing stations and on parameters not currently measured. Collection of such data strictly for evaluation purposes is often not economically feasible. However, if the evaluation of these two points was carefully integrated into the recently emphasized special surveys performed for enforcement purposes, the special survey data could serve an additional purpose and result in better location of fixed-stations and parameter coverage. The additional expense involved would be small compared to the benefits gained by the fixed-station network.

Evaluation of the third aspect of network design, sampling frequencies, can take advantage of other existing programs and procedures and be performed at a reasonable cost. Development of an evaluation procedure which utilizes existing personnel, data and data handling facilities, however, will require compromises on theoretical completeness.

The purpose of this report, therefore, is to develop a simple and easy-to-use procedure for evaluating sampling frequencies in a routine fixed-station, water-quality monitoring network used for regulatory water-quality management purposes. The procedure is based upon available data, utilizes common STORET routines for a major part of the data analysis, and employs simple, straightforward statistics via the use of several simplifying assumptions.

More specifically, the procedure uses data currently in STORET and the STORET inventory routine to compute the sample statistics for each station on each parameter. These sample statistics, based on the assumption that each parameter follows the normal distribution, are then assumed to represent the "population" parameters (i.e., they are not considered sample statistics, but rather they are assumed to represent the actual population being sampled). The population parameters are then used to examine the uniformity and size of the precisions (confidence intervals) about the water quality means.

If the precisions are not sufficiently uniform (each station supplying a relatively equal amount of information), then the total number of samples can be reallocated using a proportional sampling formula. If the precisions are not small enough for management decision making, several alternatives are presented. In addition, if there is to be a change in total samples used in the network, the effects can easily be determined by examining the effect on the precisions--both in uniformity and size.

II. CONCLUSIONS

The sampling frequency evaluation procedure presented in this report is a simple, straightforward method by which regulatory water-quality management agencies can adjust the design of their routine fixed-station monitoring networks to better meet their data and information needs. Since water quality monitoring is a statistical sampling operation, the sampling frequency evaluation procedure involves a number of statistical assumptions and utilizes basic statistical techniques.

An agency that defines its routine monitoring network data expectations in statistical terms (in this case, confidence in estimates of means) can make better use of the evaluation procedure than an agency that does not. In the latter case, however, the agency may want to use the evaluation procedure to establish its data needs or expectations in statistical terms.

The statistical assumptions made to greatly simplify the procedure should be clearly understood before the results of the evaluation are used.

The evaluation procedure is successfully demonstrated using data from two state water-quality management programs.

The evaluation procedure was developed to serve as a basic or first level of evaluation methodology. General acceptance and utilization of such basic statistical, evaluation procedures sets the stage for use of more advanced evaluation procedures when they are developed in the future. Development of such procedures should proceed in a step-by-step manner whereby one or two assumptions are removed each time. To do otherwise is to develop a methodology that appears as a complex and impractical evaluation procedure, to those who are not highly trained in statistics. This, in turn tends to discourage use of such evaluation procedures and, consequently, provides little direction to the attempts to make routine regulatory monitoring more supportive of regulatory water quality management.

III. RECOMMENDATIONS

The sampling frequency evaluation procedure is highly recommended for water-quality management agencies that have not utilized statistics in the design of their monitoring networks in the past. The procedure not only provides considerable insight into the type of data a network generates, it also introduces statistics to the agency at a level that can be easily understood.

As an agency attempts to obtain more information from its network (i.e., more statistically sound information), the assumptions used in the evaluation procedure must be removed. More information could be gained from a routine monitoring network if the types of probability distributions generally applicable were known for the water-quality parameters. At a more advanced level of statistics, more information might be gained if the exact role of time-series analysis in regulatory monitoring were precisely known. The rather low sampling frequencies in this type of monitoring obscure a quantitative definition of the contribution time-series analysis may make. Studies in the above two areas are recommended.

An overriding concern in this report has been practical utilization of the results. As future research is performed in developing more thorough evaluation procedures, it is recommended that the practical application not be forgotten. This will require knowledge of the type and level of statistics being used on a practical basis by the many water-quality management agencies and not greatly exceeding this level but carefully building upon it.

Use of the Environmental Protection Agency's STORET system by water-quality management agencies has greatly stimulated interest in data utilization. It is recommended that future work in the areas of network design and data analysis be closely coordinated with this major regulatory, water-quality management data bank.

IV. STATISTICAL BASIS

Since water quality monitoring is a statistical operation (analyzing a part to obtain information on the whole), statistics will play the major role in any attempt to evaluate how often one must sample. The level of statistics one uses to perform such an evaluation depends upon many factors (quality of data records, statistical training of personnel performing the evaluation, confidence one wants to place on the information, use of the information, etc.).

The level of statistics chosen for this evaluation procedure is more basic due to the report's emphasis on practicality. Using a more basic level of statistics involves making a number of simplifying assumptions. There are a number of ramifications that result from making the assumptions. A brief review of the assumptions will be presented below while a more detailed discussion is presented at the end of the report.

ASSUMPTIONS

The data collected on each water-quality parameter is assumed to follow a normal distribution. Making this assumption permits the evaluation procedure to utilize the existing STORET inventory routine results which include the mean and standard deviation for each water-quality parameter at each station. By assuming a normal distribution and using STORET, the evaluation procedure avoids the need for laborious and costly analysis of the raw data to determine the applicable statistical distribution for each parameter at each station.

The effects on sampling frequencies of assuming the normal distribution, rather than determining the distributions applicable, have not been evaluated in this report or in the current literature. It has been noted, however, by several authors (Beckers and Chamberlain, 1974; Lewis, 1976; Montgomery and Hart, 1974; and Sherwani and Moreau, 1975) that, in general, most water-quality parameters can be described by either the normal or log normal distributions. Thus, any error introduced would stem from using the normal distribution in a situation where the log normal was applicable. Since the evaluation procedure requires that a selection of parameters be made for inclusion in the analysis, a selection of those parameters more disposed to normality would minimize the effect of the assumption. Beyond this point, Lewis (1976) notes that ". . . the normal distribution remains a sufficient representation of C(t) [concentration of water quality] for purposes of developing monitoring network priority procedures."

If the parameters that follow a log normal distribution are known or determined, the original data for those parameters can be transformed into logarithms (thus resulting in a normally distributed set of numbers) and the evaluation procedure presented in the report can be followed. This is an option, however, only for those that have the expertise and resources available. Use of logarithms is not included in the evaluation instructions presented later in order to: (1) keep the procedures as simple as possible; (2) facilitate direct use of STORET; and (3) avoid the need to obtain and analyze large amounts of raw data.

In order to develop a basis for evaluating sampling frequencies from which rather straightforward statistics can be used, and from which comparison of alternative sampling policies can be made, the sample mean and standard deviation computed by STORET, or otherwise, are assumed to be population parameters. Use of the word "population" implies that the mean and standard deviation are known constants. Thus, from a statistical standpoint, the standard deviation or variance (the standard deviation squared) computed or estimated for each station is assumed to be the variance of the population at that station and not the variance of a sample.

The variance is determined using past data from the monitoring network (hopefully data stored in STORET in order to take advantage of STORET's inventory routine to compute the variance). Data from any number of years can be used to compute the variance, but in order to have the variance represent current conditions, it is best to use the most recent year(s). If known changes have occurred recently or are expected to occur in the near future, their impact can be estimated and incorporated into the variance for the station(s) affected. Once the variances are computed or estimated, they are assumed fixed for the remainder of the analysis.

Water quality consists of a number of parameters; consequently, determining the variance of water quality will involve determining the variance of a number of different parameters. The parameters to be used in a sampling frequency evaluation should be representative of the general water-quality conditions encountered by the monitoring program. This point will be discussed in more detail later.

PRECISION

One procedure for determining the effectiveness of a given level of sampling in a routine fixed-station monitoring network is to compute the precision of the estimate of the mean obtained from the number of samples taken at each station. The precision refers to that value which, when added and subtracted from the sample mean, establishes the range within which the true mean can be expected to fall within a given level of confidence (this range is also referred to as the confidence interval). The equation for the precision is

$$\text{PRECISION} = \frac{2\sigma_i}{\sqrt{n_i}} \qquad (1)$$

where z is the confidence coefficient, σ_i is the standard deviation of the water-quality population at station i, and n_i is the number of samples taken at the ith station over the time period considered (a year is considered as the time period in this report; therefore, n_i refers to the number of samples taken per year).

The confidence coefficient is dependent upon the level of confidence desired, but is not dependent upon the sample size since, in this situation, σ_i is not a sample statistic. For a 90% confidence level z is 1.645, while for a 95% confidence level z is 1.96. The z values for a range of confidence levels appear in most basic statistical textbooks. The selection of a confidence coefficient to use in the evaluation procedure is the responsibility of the person doing the evaluation as there are no criteria that can be used as a guide in its selection.

The precision of the estimates of annual means of the water quality parameters (i.e., the confidence interval of each parameter's annual mean) at the stations in the network gives a water-quality management agency an indication of the worth of the data that it obtains from its routine monitoring efforts. A large precision (or wide confidence interval) makes it difficult to speak very conclusively about a given parameter's average quality over the past year. On the other hand, a small precision (or narrow confidence interval) allows a much stronger statement to be made on the past year's water quality.

In an ongoing routine monitoring operation, precisions often have had little use in evaluating the monitoring effort because an agency has had a given area to be covered, a given monitoring strategy and a given budget. The sampling frequencies are set at the level permitted by the constraints. In such situations, statistics have often played a small role.

When there is a change in the constraints (such as that proposed by EPA's Standing Work Group on Water Monitoring) and an adjustment has to be made in routine sampling frequencies, the effects on precisions can be used as a basis for deciding which adjustments to make.

PROPORTIONAL SAMPLING

An evaluation of sampling frequencies and the resulting precisions considers the uniformity of the precisions obtained from the stations and the size of the precisions. Proportional sampling is introduced into the procedure to serve as a technique for obtaining more uniform precisions from a monitoring network.

By computing the precisions at all the stations in a network, different levels of precision will be noted. Those stations with a low variation in water quality will have relatively high precision for the estimate of the mean. At the same sampling frequency, a station with high variation will have low precision. By dividing the network into two or more groups and allocating frequencies according to the group's general variation in selected

water quality variables, more uniform levels of information can be obtained across the network.

If this approach is carried a step further, each station can have its sampling frequency determined by the variation in water quality that exists at its location - a type of proportional sampling. In this case, adjustments in sampling frequency are made such that each station is supplying approximately the same level of information as all the other stations (i.e., each station has the same precision).

To achieve equal precision, the following proportional allocation equation is used

$$n_i = \frac{\sigma_i^2}{\Sigma\sigma_i^2} N \qquad (2)$$

where n_i is defined as before, σ_i^2 is the variance at the ith station and N is the total number of samples to be allocated. In a network with large differences in variance, allocations according to equation 2 can be quite extreme - some stations with almost no samples and some with a very large number of samples.

This effect can be modified by basing the proportional sampling on the standard deviation. In this case, the equation becomes

$$n_i = \frac{\sigma_i}{\Sigma\sigma_i} N \qquad (3)$$

where the variables are defined as before. The result of using equation 3 is not equal precisions at all stations, but precisions which are more uniform than those obtained using equal sampling frequencies.

Since several water quality parameters will normally be involved in evaluating sampling frequencies, a separate n_i is computed for each. This results in several sampling frequencies for each station - one for each parameter considered. For practical scheduling of sample collection and analysis, the frequencies must be compromised to arrive at one sampling frequency. In this report, the compromise is achieved by simply averaging the sampling frequencies at each station.

If it is possible to establish sample-collection schedules based on the most frequently measured parameter, those parameters requiring less frequent analysis could be analyzed in the laboratory on every other sample, every fourth sample, etc. This, in effect, permits different parameters to have different sampling frequencies and avoids the often large statistical impact of compromising sampling frequencies among parameters.

V. PROCEDURE

A general procedure can be outlined for incorporating the statistics presented in the previous section into an evaluation of a water-quality monitoring network's sampling frequencies. However, before any evaluation is undertaken, it is imperative that the network being evaluated be clearly defined in terms of the stations included, the parameters important to the network's agency, the purpose of the network, the role the evaluation results will play in modifying the network's design, etc. Having a clear definition of the network and the purpose of the evaluation will greatly enhance utilization of the results of the evaluation.

The general evaluation procedure considers: (1) uniformity of precisions and (2) size of precisions. In both cases, the procedure describes alternative ways to handle conditions deemed inadequate; i.e., poor uniformity and precisions that are too large (wide confidence intervals).

EVALUATION STEPS

The general sampling frequency evaluation procedure is outlined in figure 1. The first step, numbered 1 in figure 1, involves establishing the level of confidence an agency wants from its routine, fixed-station monitoring network. This will be dependent upon the use to which the data are put within the agency. As noted earlier, there are no criteria established to assist in this determination.

The second step is selecting the water-quality parameters upon which the evaluation will be based. Although it is not impossible to include all parameters of concern, it is more economical to select representative parameters. For example, a parameter could be selected from major categories of parameters: (1) biological, (2) chemical, (3) nutrient, (4) hydrological, etc. The parameters selected should be those critical to water-quality conditions within the area being monitored. For example, a representative critical chemical parameter in a western United States monitoring network may be total dissolved solids (TDS) or conductivity.

In the third step, the total number of samples (N) available for the design period (one year is used in this report) is determined by noting the number of samples that can be processed by the available monitoring resources of the agency. Depending upon the purpose of the evaluation, either one value of N is determined or a range of N values is selected for evaluation. In the former case, the resources devoted to routine fixed-station monitoring are fixed and the question is how to get the most information from

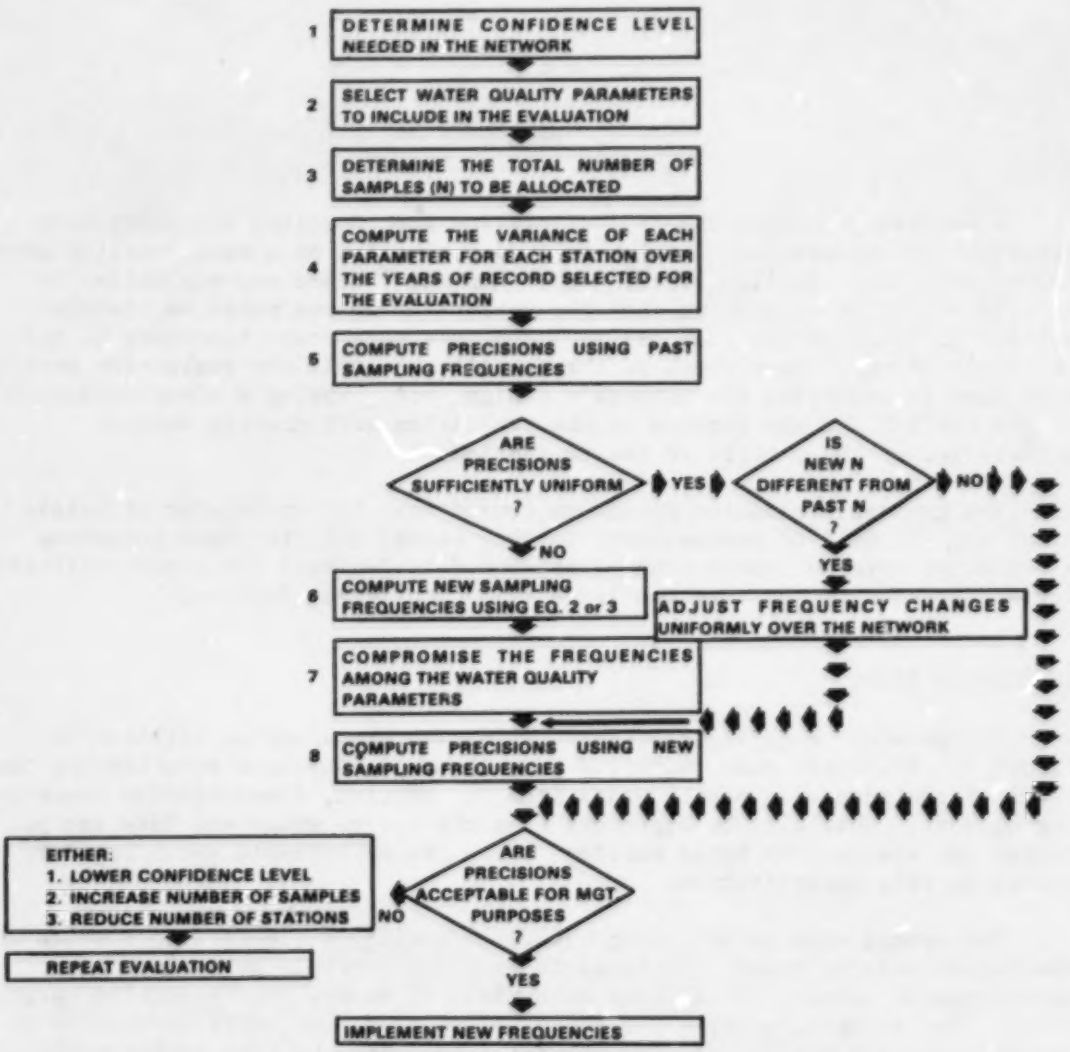
1 DETERMINE CONFIDENCE LEVEL NEEDED IN THE NETWORK
2 SELECT WATER QUALITY PARAMETERS TO INCLUDE IN THE EVALUATION
3 DETERMINE THE TOTAL NUMBER OF SAMPLES (N) TO BE ALLOCATED
4 COMPUTE THE VARIANCE OF EACH PARAMETER FOR EACH STATION OVER THE YEARS OF RECORD SELECTED FOR THE EVALUATION
5 COMPUTE PRECISIONS USING PAST SAMPLING FREQUENCIES
ARE PRECISIONS SUFFICIENTLY UNIFORM ?
YES
IS NEW N DIFFERENT FROM PAST N ?
NO
NO
YES
6 COMPUTE NEW SAMPLING FREQUENCIES USING EQ. 2 or 3
ADJUST FREQUENCY CHANGES UNIFORMLY OVER THE NETWORK
7 COMPROMISE THE FREQUENCIES AMONG THE WATER QUALITY PARAMETERS
8 COMPUTE PRECISIONS USING NEW SAMPLING FREQUENCIES
EITHER:
1. LOWER CONFIDENCE LEVEL
2. INCREASE NUMBER OF SAMPLES
3. REDUCE NUMBER OF STATIONS
NO
ARE PRECISIONS ACCEPTABLE FOR MGT. PURPOSES ?
REPEAT EVALUATION
YES
IMPLEMENT NEW FREQUENCIES

Figure 1. Flowchart of the sampling frequency evaluation procedure (numbers refer to steps in the procedure).

these resources. In the latter case, the exact amount of monitoring resources devoted to sampling may depend upon the results of the evaluation. The resources devoted to routine fixed-station monitoring may depend upon the type of information that can be obtained versus that which is needed.

The fourth step involves computing means and variances for the selected parameters at all stations included in the evaluation. It is at this step where use of STORET can tremendously reduce the computational effort required. The length of the historical record used for computing variances may vary, depending upon the quality of the record, the preference of the evaluator, and the tradeoffs between changes in quality over time versus more data for more accurate estimates. The variances computed from the historical record are assumed to be indicative of past and future quality conditions and, therefore, are assumed to be population parameters. If there are reasons to believe this is not the case, more accurate estimates of the expected variances should be substituted. If such estimates are unavailable, the station may have to be removed from the evaluation.

If, after the variances are computed, it is noted that one or two are excessively large (e.g., greater than ten times the average of the variances), these stations should be removed from the evaluation and treated separately. Excessively large values distort the evaluation procedure, often far beyond the importance of measuring the quality variation in question.

The fifth step takes the standard deviations (square root of the variance), the confidence coefficient determined in step one and the past sampling frequencies (for the past year) and computes the precisions being obtained from the network as it now exists, using equation 1. A review of these precisions gives an indication of past uniformity in the information being obtained by the monitoring network. If the precisions are sufficiently uniform for the needs of the management agency, then any adjustment in sampling frequencies can be made uniformly over the network.

If the precisions are not sufficiently uniform for the needs of the management agency, the evaluation proceeds to step six where the total number of samples is now allocated to the sampling stations through the use of equation 2 or 3. The choice of equation depends upon the level of uniformity sought. If the sampling frequencies were to be based on only one parameter, equation 2 would yield exactly equal precisions at all the stations while equation 3 would simply result in more uniform precisions than can be achieved with uniform sampling frequencies. As noted earlier, if sample collection could be geared to the parameter needing the most frequent samples, then through varying laboratory analyses the different frequencies could be permitted, resulting in exactly equal precisions using equation 2 and more uniform precisions using equation 3 rather than uniform frequencies for all parameters.

In compromising (step seven) the sampling frequencies of all the parameters at each station, the exactly equal precisions of equation 2 are lost and the more uniform precisions of equation 3 are made less uniform. With the compromising, however, the relative benefits of equation 2 versus equation 3 remains - equation 2 yields more uniformity in precisions, in general,

than equation 3. Both equations could be used with the results dictating which is more useful, given the constraints involved.

The frequency compromising used in step seven of the evaluation procedure is simple averaging, although the parameters could be weighted to give more emphasis to a parameter particularly critical in the area being monitored.

New precisions are computed in step eight using the compromised sampling frequencies from step seven. As noted above, using compromised frequencies results in compromised precisions. If the frequencies have not been allocated for uniformity, but rather allocated uniformly, the new precisions are computed at this step. In either case, the new precisions must be reviewed to determine if the precisions (confidence intervals) are sufficient for management purposes.

PERCENTAGE CHANGE INDEX

At this point in the evaluation procedure, it may be quite helpful to be able to compare <u>average</u> precisions over the entire network for the various water-quality parameters rather than station by station. The effects on average precisions of using one allocation method versus another (equation 3 allocations versus equation 2 allocations versus uniform allocations), or of using one level of sampling versus another, will be much easier to visualize on a total network basis if average network precisions are available.

One approach is simply to compute the mean and standard deviation of the precisions across all the stations for each water-quality parameter. Thus, if more uniformity of precisions across stations is being sought by a new allocation procedure (equation 2 or 3), a comparison of the standard deviation of the precisions obtained with constant sampling frequencies with those obtained with equation 2 or 3 will reveal the amount of improvement that can be achieved. Likewise, if tighter precisions are sought by increasing the total number of samples available, comparing the mean of the precisions of the old level of sampling with that of the new will indicate the amount of improvement that can be obtained. If a reduction in sampling must take place, the effect can be determined by comparing means of the precisions.

A further aggregation of the means and standard deviations of the precisions, which includes all the water-quality parameters used for the evaluations, will permit one overall number (index) to be developed which will indicate the level of improvement or degradation in the precisions when changes in sampling frequencies are being evaluated. For example, what is the overall improvement in precisions when samples are allocated for uniform precisions rather than for uniform frequencies?

Development of such an index is based on the sum of the percentage changes that occur in each parameter's precision from one design to the next. Thus, while a negative change may occur in one parameter and a positive change in all the others considered, the percentage change index gives an

overall indication of change, either negative or positive, depending upon the magnitude of change of the parameters in the sum.

A percentage change index can be computed for the mean of the precisions or the standard deviation of the precisions. The equation for the percentage change index based on the mean of the precisions (PCI_m) is

$$PCI_m = \frac{\sum_{i=1}^{p} \frac{OPM_i - NPM_i}{OPM_i}}{p} \times 100 \qquad (4)$$

where OPM_i is the old sampling-frequency precision mean for the ith parameter, NPM_i is the new precision mean, and p is the total number of water-quality parameters included in the evaluation.

The equation for the percentage change index based on the standard deviations of the precisions (PCI_{sd}) is

$$PCI_{sd} = \frac{\sum_{i=1}^{p} \frac{OPSD_i - NPSD_i}{OPSD_i}}{p} \times 100 \qquad (5)$$

where $OPSD_i$ is the old sampling frequency precision standard deviation of the ith parameter, $NPSD_i$ is the new precision standard deviation, and p is defined as above.

PRECISION IMPROVEMENT ALTERNATIVES

If, after comparing the individual precisions and the percentage change indexes, it is decided that the precisions are adequate for management purposes, then the sampling frequencies that generated these precisions are implemented. However, if it is deemed that the precisions are not adequate, then the monitoring data will not be sufficient to support the management agency.

If this latter situation exists, the agency must either accept the data limitations and organize its management strategy to match the information it can afford, or it can do one of three things to improve the precisions: (1) lower the confidence level, (2) increase the number of samples, or (3) reduce the number of stations. Each of these actions would increase the precision.

Reducing the confidence in the precision estimate is not recommended unless the management program decides it can effectively operate with a lower level of confidence in the estimates of quality obtained from its monitoring system. Lowering the confidence level just shifts the data limitation rather than corrects it.

Increasing a monitoring budget is often difficult, if not impossible. Given the information from the evaluation, however, it may be easier to justify an increase in a monitoring budget since the budget increase can be directly related to an increase in the precision of the network. In this situation, an average precision increase over the entire network may be more readily understood.

If an increase in budget is not possible, a reduction in the number of stations is the only remaining alternative for increasing the network's precision. Such an action trades spatial coverage for more precision at the remaining stations. The results (sampling frequencies) of the evaluation procedure (step seven) indicate which stations have a low quality variation (indicated by low frequencies) and which may, therefore, be eliminated from routine monitoring, especially if the quality mean is well below water quality standards applicable at that station. In general, such a view of the sampling frequencies allocated by variation permits the evaluation procedure to identify stations that may be of questionable value. It cannot, however, identify where stations are needed.

If any of the above changes are made, the evaluation procedure is repeated. The exact portion of the procedure repeated depends upon the change made. Through successive iterations around such changes, a large amount of information can be obtained relative to tradeoffs between monitoring precision, spatial coverage, and monitoring budget.

Once the precisions are deemed acceptable, the computed sampling frequencies must be implemented. This first involves rounding the frequencies to integer values. Next the frequencies must be integrated into practical and economical sample collection routes and schedules, laboratory analysis schedules, etc. In the process of working the computed frequencies into an operational monitoring system, there will, no doubt, be further compromises in the frequencies. Thus, the computed frequencies actually serve only as a guide for establishing sampling frequencies in a regulatory water-quality monitoring network.

VI. APPLICATION

Applications of the sampling frequency evaluation procedure are developed using data from the Water Quality Control Division of the Colorado Department of Health and the Minnesota Pollution Control Agency. The applications are established only to illustrate the evaluation procedure and do not relate to the practical design of either the Colorado or Minnesota monitoring networks.

The Colorado application includes an evaluation of the effects of using equation 2 versus equation 3 for allocating samples while the Minnesota application includes a sensitivity analysis of the total number of samples available for allocation. In addition, the Colorado application was performed using a Hewlett-Packard programmable pocket calculator (Model 65) while the Minnesota application was performed on an IBM computer using a FØRTRAN program.

In initial tests of the evaluation procedure, it was noted that excessively large values of variance (or standard deviation) tended to completely dominate the allocation of samples in step six. Upon checking the large values, it was noted that they were due to unusual situations which should be treated separately. Consequently, limits on the variance were established for the parameters involved in the applications. This resulted in one station being excluded in each of the applications. To illustrate, in the Colorado and Minnesota applications, conductance was limited to a variance of 1.0×10^8 micromhos or a standard deviation of 10,000 micromhos.

By reviewing the variances or standard deviations prior to initiating the evaluation, any highly unusual situations can be identified. Removal of such stations from the evaluation prevents a distortion of the results and allows the special stations to be treated in a manner which better deals with the special nature of the pollution problem causing the condition.

COLORADO APPLICATION

Colorado operates a routine, fixed-station monitoring network that consists of a primary set of stations and a secondary set - the distinction being a sampling frequency of 24 samples per year for primary stations and 6 samples per year for the secondary stations. Since each sub-network has a different information goal, each should be evaluated independently of the other.

Only the primary stations will be considered in this application. The stations included in this application are not exactly those in Colorado's network. Again, the use of Colorado's data is for demonstration purposes only and is not intended to reflect actual conditions.

The Colorado evaluation application assumes that the same number of total samples will be used in the next year as has been used in the past. The purpose of the evaluation is to allocate the samples so that a more uniform level of information is obtained from the stations in the network.

STEP 1 - A 90-percent confidence level was arbitrarily selected for this application. The confidence coefficient (e) for a 90-percent confidence level is 1.645. The implication of this is that the means of water quality can, 90 percent of the time, be expected to lie within the confidence interval computed from the precisions.

STEP 2 - Three water-quality parameters were arbitrarily chosen for the Colorado application: (1) conductivity as a representative chemical parameter, (2) biochemical oxygen demand (BOD) as a representative biological parameter, and (3) nitrate-nitrogen (NO_3-N) as a representative nutrient parameter.

STEP 3 - Since the purpose of the evaluation is simply to determine how to reallocate the existing samples in a manner which yields a more uniform level of information for the stations, the total number of samples will be the same as in the past (576).

STEP 4 - Computation of variances and standard deviations was accomplished through use of the standard STORET inventory routine (PGM = INVENT). The variances and standard deviations were computed by STORET using three years of record (1973-1975). The statistics obtained from the STORET printout are assumed to be the population parameters as described in Section IV. The means and standard deviations are presented in table 1; the means are for reference only as they are not used in the evaluation procedures.

STEP 5 - The precisions obtained using the uniform, 24 samples per year sampling frequency are computed using equation 1, the e value from step one, and the standard deviations from step four. The precisions obtained for the three water-quality parameters are presented in table 2.

The precisions vary over a wide range as did the standard deviations in table 1. To see if the precisions can be made more uniform, the evaluation proceeds to the next step.

STEP 6 - Allocation of samples is first computed for each parameter using equation 3 and then using equation 2. The latter equation assures that the precisions obtained for each parameter are equal while the former results in more uniformity than constant sampling over the network, but not equal precisions for each parameter. If, in using equation 2, the network had a sampling frequency determined only by conductivity, the precision of conductivity at all the stations would be 110.90 micromhos. Likewise, if only BOD were used, the BOD precision at all stations would be 2.35 mg/l. For

TABLE 1. ASSUMED POPULATION STATISTICS FOR COLORADO APPLICATION
(Means are presented for information only)

Station Number	Conductivity		BOD		NO_3 - N	
	Mean (Micromhos)	Standard Deviation (Micromhos)	Mean (mg/l)	Standard Deviation (mg/l)	Mean (mg/l)	Standard Deviation (mg/l)
1	4136.19	867.75	2.25	1.28	1.54	0.59
2	1431.43	436.05	4.02	1.81	2.59	0.96
3	759.39	238.28	4.29	2.82	2.04	0.97
4	723.75	146.90	19.96	14.77	1.45	1.74
5	1410.39	246.68	10.35	12.66	4.43	1.44
6	962.87	251.78	15.69	9.16	2.37	2.42
7	354.34	74.32	2.21	1.25	2.15	1.86
8	1554.15	277.62	11.37	12.34	4.16	1.55
9	1791.18	426.76	8.68	8.21	2.27	1.15
10	926.80	371.45	10.34	9.91	2.01	1.14
11	573.34	204.84	6.88	3.32	1.42	1.10
12	681.20	257.64	7.32	3.81	1.82	1.71
13	237.11	87.64	2.32	1.28	0.42	0.34
14	383.64	135.53	2.87	1.27	0.56	0.92
15	339.60	93.97	1.38	0.63	0.17	0.19
16	779.86	278.55	1.64	1.05	0.28	0.38
17	1068.69	371.64	1.94	1.04	0.77	0.30
18	692.58	303.44	1.49	0.80	0.33	0.37
19	523.77	156.72	1.42	0.66	0.24	0.17
20	993.68	421.96	1.84	0.77	1.09	0.60
21	1623.06	434.57	2.06	0.99	2.73	1.05
22	353.49	200.40	1.97	1.18	0.46	0.37
23	353.06	149.84	3.66	2.69	0.39	0.38
24	2263.76	405.58	13.32	18.31	2.68	1.37

TABLE 2 SAMPLING FREQUENCIES AND PRECISIONS FOR THE COLORADO NETWORK

Station Number	Uniform	Sampling Frequencies (Samples per Year)		Precisions								
				Conductivity (Micromhos)			BOD (mg/l)			NO_3-N (mg/l)		
		Computed by Eq. 3	Computed by Eq. 2	Uniform	Eq. 3	Eq. 2	Uniform	Eq. 3	Eq. 2	Uniform	Eq. 3	Eq. 2
1	24	31.45	57.64	291.38	254.54	188.02	0.43	0.38	0.28	0.20	0.17	0.13
2	24	23.37	20.27	146.42	148.38	159.32	0.61	0.61	0.66	0.32	0.33	0.35
3	24	19.57	11.29	80.01	88.61	116.66	0.95	1.05	1.38	0.32	0.36	0.47
4	24	43.96	56.22	49.32	36.45	32.23	4.96	3.66	3.24	0.58	0.43	0.38
5	24	40.62	43.64	82.83	63.67	61.43	4.25	3.27	3.15	0.48	0.37	0.36
6	24	42.92	54.87	84.54	63.22	55.91	3.08	2.30	2.03	0.81	0.61	0.54
7	24	19.73	22.22	24.96	27.53	25.94	0.42	0.46	0.44	0.62	0.69	0.65
8	24	41.88	45.62	93.22	70.57	67.61	4.14	3.14	3.00	0.52	0.39	0.38
9	24	35.67	32.70	143.30	117.54	122.76	2.76	2.26	2.36	0.39	0.32	0.33
10	24	36.88	34.25	124.73	100.62	104.41	3.33	2.68	2.79	0.38	0.31	0.32
11	24	20.61	12.43	68.78	74.22	95.57	1.11	1.20	1.55	0.37	0.40	0.51
12	24	27.99	25.42	86.51	80.11	84.06	1.28	1.18	1.24	0.57	0.53	0.56
13	24	7.48	1.55	29.43	52.72	115.80	0.43	0.77	1.68	0.11	0.20	0.45
14	24	13.66	6.90	45.51	60.32	84.88	0.43	0.57	0.80	0.31	0.41	0.58
15	24	5.33	0.94	31.55	66.95	159.43	0.21	0.45	1.07	0.07	0.14	0.33
16	24	12.79	6.78	93.53	128.12	175.97	0.35	0.48	0.66	0.13	0.18	0.24
17	24	14.46	10.76	124.79	160.77	186.37	0.35	0.45	0.52	0.09	0.12	0.14
18	24	12.98	7.72	101.89	138.55	179.65	0.27	0.37	0.47	0.12	0.17	0.22
19	24	6.94	2.05	52.62	97.93	180.05	0.22	0.41	0.75	0.06	0.10	0.19
20	24	18.12	15.37	141.69	163.06	177.05	0.26	0.30	0.32	0.20	0.23	0.25
21	24	22.67	20.91	145.92	150.14	156.33	0.33	0.34	0.36	0.35	0.36	0.38
22	24	10.75	4.04	67.29	100.68	164.01	0.40	0.59	0.96	0.12	0.19	0.30
23	24	11.98	3.74	50.31	71.21	127.63	0.90	1.28	2.30	0.13	0.18	0.32
24	24	54.19	78.67	136.19	90.63	75.22	6.15	4.09	3.40	0.46	0.31	0.25
TOTAL	576	576	576									
		Mean		95.70	100.27	120.68	1.57	1.35	1.48	0.32	0.31	0.36
		Standard	Deviation	57.25	50.58	51.60	1.78	1.21	1.05	0.20	0.15	0.14

NO_3-N, the precision would be 0.38 mg/l. These, in other words, are the precisions that would be obtained if there were no compromising. Varying analytical determinations in the laboratory would help approach these precisions.

It is possible to collect different frequencies for different parameters, but often this is not practical in routine monitoring; therefore, the frequencies for the parameters will be compromised in this example. By compromising the sampling frequencies and equal precisions gained by use of equation 2, unequal precisions for the parameters result. Also, the more uniform precisions gained by use of equation 3 are reduced in uniformity by compromising.

STEP 7 - The frequencies computed for the individual parameters are compromised, by simple averaging, to yield one frequency at each station. These compromised frequencies are presented in table 2 for allocations made by both equations 3 and 2. In both cases, the total samples allocated sum to 576 as established in step three since there is no change in the number of samples to be allocated in the next year.

STEP 8 - The new, more uniform precisions for the water quality parameters are computed using the new sampling frequencies, equation 1, the confidence coefficient established in step one and the standard deviations from step four. The precisions for both equation 3 and 2 allocations are presented in table 2.

A review of the individual station results in table 2 reveals that, in general, the sampling frequencies computed by equation 3 result in slightly more uniform precisions than the uniform frequency while those computed by equation 2 have more of the large precision extremes brought back into line with the other precisions (conductivity at station 1 and BOD at station 24). In both cases, there is a general tendency for the large precisions to be reduced and the small precisions to be expanded. As would be expected, this tendency is greater when equation 2 is used to allocate samples. The sampling frequencies also reflect this, as those computed by equation 2 are more extreme than those of equation 3 - these extremes are needed to bring the precision at high variation stations more into line with the other precisions.

To further compare the improvements in uniformity, the standard deviations of the precisions are computed and presented in table 2. The standard deviations of equation 2 and 3 precisions are better for all parameters than the constant frequency precisions. Thus, there is more uniformity when samples are allocated by equations 2 or 3.

To measure exactly how much overall improvement there is, the standard deviation percentage change index will be used. The PCI_{sd} for equation 3 frequencies over uniform frequencies is 23 percent. For equation 2 frequencies over uniform frequencies the PCI_{sd} is 27 percent. The major improvement is achieved using equation 3 to allocate samples. The additional improvement gained by using equation 2 does not appear to justify using the extreme frequencies it generated. Whether the 23 percent more uniformity justifies

changing from a constant frequency can only be decided by the agency using the data.

The results in table 2 can also be used in deciding which stations should be removed, if the precisions are not adequate. The frequencies computed by equations 2 and 3 yield a common basis for comparison of the water-quality variability among the stations. Those stations with really low frequencies have a relatively low variability in all the parameters. If the mean quality is not near the water-quality standard, the results in table 2 may be sufficient justification for a station's removal from the network. Stations 13, 15 and 19 in table 2 have very low frequencies compared to the average of 24 samples per station.

MINNESOTA APPLICATION

Minnesota, as defined for purposes of this application, operates a routine fixed-station monitoring network of 80 stations, each of which is sampled 12 times per year. The Minnesota sampling frequency evaluation application assumes that there is a desire to know what effect an increase or decrease in sampling frequency would have on the network. The application will include a reallocation of samples for more uniformity (equation 2 will be used).

STEP 1 - As with the previous application, the 90 percent confidence level is used.

STEP 2 - Three water quality parameters selected for the application are: (1) conductivity as a representative chemical parameter, (2) dissolved oxygen (DO) as a representative "biological" parameter, and (3) organic nitrogen (ON) as a representative nutrient parameter.

STEP 3 - Since the purpose of the evaluation is to examine the effects of any increases or decreases in sampling frequencies, a range of total samples will be considered. The range will consider reductions to an average of 6 and 9 samples per station per year and increases to an average of 15, 18, 21 and 24 samples per year. Of the 80 stations used in this application, one station was eliminated for having an excessively large organic nitrogen variance; therefore, the corresponding total number of samples considered is 474, 711, 948 (for the average 12 samples per year), 1,185, 1,422, 1,659, and 1,896.

STEP 4 - Again the variances and standard deviations are computed via STORET. Rather than printing it, the output is instead placed in a data set. The data set is then edited to delete unwanted parameters, summary tables, etc. The data are placed in a data set to permit the use of a FØRTRAN program to perform the computations involved in the application.

The variances and standard deviations are computed using three years of record (1974-1976). Again, these statistics are assumed to be the population statistics.

STEPS 5 - 8 - These four steps are performed by the FØRTRAN program. In addition, a number of "checks" are added to the program to ensure that the proper data are used. A listing of the program is presented in Appendix A. The program is designed to handle this particular application and, although the program is general in most aspects, certain portions would have to be changed for other applications.

In table 3, the results of the FØRTRAN program are presented for the allocation of the same total number of samples (948) as in the past. The comparison is between the constant sampling frequency among stations (12 samples per year per station) and the proportional allocation which results in more uniform precisions using equation 2. The improvement in uniformity of the precisions is 31 percent.

Data similar to that in table 3 were obtained for each of the other sample totals considered. In each case, the proportional allocation was used to allocate the samples and these results were then compared with the results of the 12 samples per year per station presented in table 3.

To illustrate the general effect of changing the level of sampling from the 948 samples per year level with a constant 12 samples per year per station, the percentage change index on the means (PCI_m) is computed for each level of sampling considered. The PCI_m's are presented in table 4. Thus, if the sampling level is reduced by one-half and if the 474 samples are proportionally allocated to achieve more uniform precisions, a reduction in the precision means of 37.02 percent can be expected. If 237 samples are added to the present 948 samples and the resulting 1,185 samples are proportionally allocated to achieve more uniform precisions, an improvement in precision means of 13.34 percent is achieved over the current 948 samples, allocated uniformly to the stations.

To examine changes in the sampling level only, the PCI_m's can be subtracted from each other. This results in a measure of effect of a change per 237 samples (the samples are assumed to be allocated proportionally at all sampling levels). These percent changes are presented in the third column of table 4. Thus, if the current sampling level (948) is reduced by one-half, reduction in the precision means is 40.13 percent (25.14 + 14.99). An addition of 237 samples to the current 948 samples would improve the precision means by 10.23 percent.

The changes in precision means per 237 samples, presented in table 4, illustrate the principle of diminishing returns. At a low level of sampling (474 samples per year), the addition of 237 samples yields an improvement of 25.14 percent while at a higher level of sampling (1,659 samples per year), the addition of 237 samples yields an improvement of only 4.73 percent.

It is only a short step from the information in table 4 to a cost-benefit analysis. A cost is associated with collecting and processing each group of 237 samples. This cost can then be associated with the additional benefit or effectiveness gained by adding the 237 samples. Such information can be extremely useful in water-quality management program planning.

TABLE 3. EXAMPLE OF SAMPLING FREQUENCIES AND PRECISIONS FOR THE MINNESOTA NETWORK (NEW N EQUAL TO PAST N). (continued)

STATION NO.	STATION DESCRIPTION	OLD FREQ	NEW FREQ	CONDUCTVY OLD PREC	CONDUCTVY NEW PREC	DO OLD PREC	DO NEW PREC	ORG N OLD PREC	ORG N NEW PREC
1	CEDAR RIVER 2.5 MI. W. OF LYLE	12.00	12.02	58.874	58.838	1.127	1.126	0.308	0.308
2	CEDAR RIVER 3 MI S. OF AUSTIN	12.00	14.07	60.647	56.813	1.053	0.972	0.509	0.470
3	FOUNTAIN L-USH-16 AT ALBERT LEA	12.00	14.12	51.646	47.612	2.174	2.084	0.306	0.282
4	SHELLROCK R. W OF GORDONSVILLE	12.00	23.60	98.449	64.502	2.091	1.491	0.822	0.566
5	DES MOINES R.-W FORK.PETERSBURG	12.00	19.54	224.924	176.032	1.250	0.978	0.305	0.239
6	RAINY RIVER BRIDGE AT BAUDETTE	12.00	8.30	64.635	77.714	0.909	1.093	0.144	0.178
7	RAINY R. AT INTERNATIONAL FALLS	12.00	5.15	5.644	8.614	1.068	1.630	0.096	0.146
8	RAINY R.PUBLIC ACCESS.INT FALLS	12.00	10.27	30.261	25.984	1.163	0.998	0.729	0.626
9	LAKE SUPERIOR AT SILVER BAY	12.00	4.00	8.683	16.896	0.540	0.926	0.127	0.217
10	ST LOUIS R. SH-23 AT FOND DU LAC	12.00	8.17	27.580	33.422	1.428	1.731	0.149	0.180
11	ST. LOUIS R. USH-2 BY BROOKSTON	12.00	8.08	66.125	76.857	1.162	1.351	0.128	0.149
12	PIPESTONE CREEK S W OF PIESTONE	12.00	25.02	249.663	172.916	1.748	1.205	0.488	0.332
13	ROCK RIVER S OF LUVERNE	12.00	15.53	90.618	79.664	1.887	1.659	0.334	0.294
14	BLUE EARTH RIVER N OF WINNEBAGO	12.00	15.52	125.368	110.232	1.484	1.304	0.367	0.270
15	COTTONWOOD R. SH-16 AT NEW ULM	12.00	11.57	88.937	82.442	0.976	0.996	0.298	0.302
16	LAC QUI PARLE R.BY LAC QUI PARLE	12.00	16.09	164.717	143.975	1.332	1.150	0.244	0.211
17	MINNESOTA R.SH-36 IN BLOOMINGTON	12.00	12.43	70.778	69.532	1.130	1.110	0.343	0.347
18	MINNESOTA R. SH-19 AT HENDERSON	12.00	12.66	72.758	70.848	1.297	1.224	0.335	0.326
19	MINNESOTA R. SH-22 AT ST. PETER	12.00	12.65	85.315	83.184	1.078	1.058	0.332	0.323
20	MINNESOTA R.CSAH-24 AT COURTLAND	12.00	12.79	87.320	84.586	1.492	1.487	0.256	0.248
21	MINNESOTA R. USH-71 AT MORTON	12.00	11.10	98.869	101.892	1.082	1.042	0.266	0.214
22	MINN R. CSAH-40 BRIDGE AT MILAN	12.00	14.03	82.911	76.681	1.719	1.586	0.296	0.274
23	POMME DE TERRE R. AT APPLETON	12.00	12.89	90.852	86.981	1.113	1.074	0.325	0.314
24	WATONWAN R. W. OF GARDEN CITY	12.00	12.72	75.834	73.648	1.345	1.306	0.311	0.302
25	YELLOW MEDICINE R.-GRANITE FALLS	12.00	10.93	87.376	91.545	0.909	0.952	0.248	0.260
26	CANNON R. USH-61 W OF RED WING	12.00	11.36	46.118	47.357	1.229	1.262	0.342	0.351
27	CROW RIVER CSAH-36 AT DAYTON	12.00	10.80	48.788	51.335	1.016	1.071	0.341	0.359
28	CROW R. SH-22 1 MI NW OF BISCAY	12.00	16.83	141.952	136.733	1.304	1.101	0.314	0.265
29	CROW WING R. USH-210 BY PILLAGER	12.00	7.36	27.842	35.554	1.266	1.617	0.128	0.164
30	O'BRIEN BROOK CAR-12.PENGILLY	12.00	7.53	45.894	56.925	1.101	1.390	0.119	0.150
31	RUM RIVER USH-10 AT ANOKA	12.00	8.54	29.152	34.557	1.264	1.499	0.202	0.240
32	RUM RIVER CAR-5 AT ISANTI	12.00	8.48	34.394	40.987	1.222	1.453	0.191	0.227
33	ROOT RIVER SH-26 E. OF HOKAH	12.00	15.59	19.248	16.888	0.961	0.843	0.761	0.668
34	SAUK RIVER CSAH-1 SAUK RAPIDS	12.00	9.64	39.858	43.566	1.115	1.244	0.274	0.306
35	STRAIGHT RIVER BY CLINTON FALLS	12.00	10.63	75.911	80.667	1.135	1.207	0.217	0.231
36	MISSISSIPPI R. AT SAUK RAPIDS	12.00	7.98	32.180	39.469	1.144	1.403	0.161	0.222
37	MISSISSIPPI R. AT LA CROSSE	12.00	7.65	18.647	23.350	1.298	1.616	0.172	0.216
38	MISSISSIPPI R. AT HASTINGS	12.00	11.66	45.315	46.885	1.209	1.229	0.364	0.378
39	MISSISSIPPI R. AT FRIDLEY	12.00	8.89	35.037	42.671	1.223	1.449	0.143	0.148
40	MISSISSIPPI R. AT CLEARWATER	12.00	7.19	35.842	46.313	1.060	1.378	0.135	0.174
41	MISSISSIPPI R. BY ROYALTON	12.00	6.47	29.799	40.571	1.083	1.475	0.102	0.139
42	MISSISSIPPI R. AT CAMP RIPLEY	12.00	6.77	27.166	36.171	1.047	1.394	0.138	0.184
43	MISSISSIPPI RIVER AT JACOBSON	12.00	6.43	32.183	43.951	1.083	1.370	0.109	0.149
44	MISSISSIPPI R. S.W. OF COHASSET	12.00	6.48	23.855	32.461	1.186	1.414	0.108	0.136
45	MISSISSIPPI R. EAST OF RENEOJI	12.00	5.44	14.183	20.582	0.968	1.438	0.092	0.137

TABLE 3. (continued) EXAMPLE OF SAMPLING FREQUENICES AND PRECISIONS FOR THE MINNESOTA NETWORK (NEW N EQUAL TO PAST N).

46	MISSISSIPPI R. BY LAKE ITASCA	12.00	6.89	27.788	36.683	1.205	1.590	0.110	0.146
47	OTTERTAIL RIVER AT BRECKENRIDGE	12.00	13.38	68.604	64.970	1.486	1.331	0.364	0.345
48	RED LAKE RIVER-EAST GRAND FORKS	12.00	8.71	26.489	31.885	1.299	1.524	0.215	0.252
49	RED R. CSAH-18 BR AT BRUSHVALE	12.00	11.77	104.329	105.361	1.278	1.291	0.171	0.173
50	WATERWORKS INTAKE BR. FORKS, ND	12.00	12.04	75.983	75.782	1.514	1.510	0.232	0.231
51	RED R. CSAH-39 BR W OF PERLEY MN	12.00	13.80	114.158	110.164	1.264	1.178	0.264	0.246
52	RED R. MAIN & FIRST AV BR. FARGO	12.00	11.23	85.348	88.210	1.477	1.526	0.156	0.160
53	BOISE DE SIOUX R.NR BRECKENRIDGE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
54	BUFFALO R. USH-75 AT GEORGETOWN	12.00	28.57	416.395	269.866	1.512	0.980	0.228	0.148
55	WILD RICE R. USH-75 N OF HENDRUM	12.00	12.53	74.507	72.923	1.369	1.340	0.297	0.291
56	KETTLE R. CSAH-48 E OF HINCLEY	12.00	7.72	27.648	28.237	1.374	1.713	0.146	0.182
57	ST. CROIX R. RR BR NEAR HUDSON	12.00	7.72	23.343	29.134	1.093	1.363	0.203	0.253
58	ST CROIX R. AT TAYLORS FALLS	12.00	5.78	18.553	20.727	0.938	1.351	0.124	0.178
59	ST. CROIX R. W OF DANBURY. WS	12.00	5.74	13.185	19.057	1.079	1.559	0.109	0.157
60	MISS R. 5 MI SE OF GRAND RAPIDS	12.00	6.95	31.103	40.873	1.147	1.508	0.116	0.152
61	SWAN RIVER AT JACOBSON	12.00	6.20	30.401	42.277	1.086	1.399	0.099	0.138
62	LONG PRAIRIE R. USH-10 S MOTLEY	12.00	9.67	37.054	41.284	1.726	1.917	0.155	0.173
63	BEAVER R. N OF BEAVER BAY	12.00	6.79	25.224	33.539	1.173	1.559	0.119	0.158
64	ST LOUIS BAY AT DULUTH-SUPERIOR	12.00	8.01	23.723	29.033	1.476	1.807	0.140	0.172
65	SAUK R. CSAH-31 S OF NEW MUNICH	12.00	9.41	54.936	62.021	1.271	1.434	0.176	0.199
66	BUFFALO CR. USH-212 W OF PLATO	12.00	48.05	683.858	341.755	1.914	0.957	0.548	0.284
67	CENTER CR. 1 MI N OF FAIRMONT	12.00	16.38	181.183	154.994	1.292	1.186	0.226	0.193
68	COTTONWOOD R. SE OF SPRINGFIELD	12.00	12.99	187.498	183.310	1.350	1.298	0.226	0.217
69	CHIPPEWA R. SH-40 EAST OF MILAN	12.00	12.01	91.731	91.688	1.259	1.256	0.231	0.231
70	REDWOOD R. CSAH-101 AT N REDWOOD	12.00	19.64	237.695	185.785	1.190	0.930	0.241	0.219
71	LE SUEUR R. 5 MI SW OF WASECA	12.00	14.84	152.334	136.972	1.376	1.237	0.199	0.179
72	WHITEWATER R. CR-1 NW OF UTICA	12.00	9.37	25.642	29.626	1.257	1.423	0.269	0.305
73	VERMILLION R. N OF FARMINGTON	12.00	9.65	67.073	74.794	0.792	0.883	0.253	0.283
74	OKABENA CR. CSAH-9 BR AT OKABENA	12.00	47.05	422.327	213.285	2.484	1.255	1.219	0.616
75	MISS R. AT L & D 5 N OF WINONA	12.00	8.07	16.950	20.663	1.313	1.660	0.201	0.244
76	RAINY R. AT OUTLET OF RAINY LAKE	12.00	4.93	4.121	6.427	0.979	1.528	0.105	0.164
77	ST LOUIS R. CSAH-27 W OF ZIM	12.00	7.25	44.871	57.740	0.932	1.199	0.117	0.176
78	E SWAN R. CR-444 SE OF HIBBING	12.00	9.67	75.342	83.914	0.976	1.087	0.190	0.211
79	CANNON RIVER AT RANDOLPH	12.00	12.17	52.935	52.565	1.814	1.807	0.417	0.414
80	ZUMBRO R. CSAH-14 N OF ROCHESTER	12.00	11.92	80.168	80.371	0.847	0.850	0.349	0.350
	TOTAL NUMBER OF SAMPLES	948.00	948.00						
	PRECISION MEANS			81.164	71.562	1.235	1.299	0.260	0.253
	PRECISION STANDARD DEVIATIONS			101.914	57.349	0.338	0.295	0.183	0.116

TABLE 4. IMPACT OF CHANGING THE SAMPLING FREQUENCY -- MINNESOTA APPLICATION

Total Number of Samples to be Allocated	PCI_m (Change over the current constant sampling frequencies)	Percent Change per 237 Samples
474	-37.02	
		25.14
711	-11.88	
		14.99
948	3.11	
		10.23
1,185	13.34	
		7.55
1,422	20.89	
		5.87
1,659	16.76	
		4.73
1,896	31.49	

VII. DISCUSSION

The applications have illustrated how the sampling frequency evaluation procedure can be used to obtain more uniform levels of information from a network and to provide quantitative information on the effects of changes in sampling frequency. Considerable insight can be gained on a network by simply reviewing the precisions computed in the initial phases of the evaluation.

STATISTICAL ASSUMPTIONS

Correct interpretation of the results of the evaluation procedure requires a clear understanding of the assumptions. The assumption that past means and standard deviations are population parameters is the most important. This assumption permits the evaluation procedure to proceed in a rather straightforward manner. Implications of the assumption are that future water-quality conditions will be similar to past conditions.

Beyond assuming that past sample statistics are acceptable population parameter estimates, the water-quality parameters used in the evaluations are assumed to follow a normal distribution. In the absence of more detailed data, this is not an unreasonable assumption (Lewis, 1976). Normal statistics are easy to use and can be readily understood by users of the evaluation procedure, thus greatly facilitating the incorporation of statistics into monitoring efforts where few statistics have existed in the past. There are studies dealing with specific situations that have shown that other distributions may be more applicable, but these findings are not generalized enough to justify using a distribution other than normal in all cases. As more conclusive information on water-quality parameter frequency distributions is obtained, it can be incorporated into the procedure.

In addition to assuming the normal distribution, it is assumed that the sampling has been performed in a "random" manner and that the samples are "independent." Since the "population" being sampled is a time series, a true evaluation of the random sample and independent observation assumptions is difficult unless a large amount of data is taken and carefully examined. Since a general purpose network, such as is being dealt with here, covers a large area and has relatively low sampling frequencies, it is not practical to perform the detailed analysis on every station.

Variation in water quality over a year's time frame is, in general, a function of several factors: (1) long term trends, (2) seasonal changes, and (3) random variations. No attempt has been made to break the overall

variation into the above components. Thus, the evaluation procedure included non-random variation as well as random variation. This fact results in higher frequencies than would normally be used to measure only random variation.

The above aspects of statistics and water-quality monitoring have been discussed by several authors. Perhaps the more practical of the discussions have been presented by Montgomery and Hart (1974) and Sherwani and Moreau (1975). Sanders (1974) and Steele (1971) present somewhat more theoretical discussions that also point out the impact of the above statistical assumptions. Ward, Nielsen and Bundgaard-Nielsen (1976) summarize a number of the above discussions and also present a detailed review of proportional and stratified sampling as it is related to the design of water-quality monitoring systems.

When the evaluation applications were set up with the Colorado and Minnesota data, 3 years of past records were used to compute the standard deviations. The standard deviations could be computed with only the latest year's record, if this were deemed necessary.

UNIFORM INFORMATION LEVELS

The goal of uniform levels of information from stations in a monitoring network may be desirable, but the use of uniform (constant) sampling frequencies is often more practical. Any compromise between the two competing objectives may be easier to resolve following an evaluation as proposed herein.

The goal of uniform information levels has rarely been used in regulatory water-quality monitoring in the past. The concept of equal information from stations in a water-quantity network has been discussed by several authors (e.g., Matalas, 1968; and Yevjevich, 1972). Sherwani and Moreau (1975) discuss the role of equal "information content" as it relates to water-quality monitoring.

In using the uniform (or equal) information goal in a regulatory monitoring network, several philosophical questions are raised. Most of these can be dealt with by first carefully defining, in statistical terms, exactly what is expected of a monitoring network. If the expectations involve obtaining statistically sound information, then it is possible that the monitoring network design can benefit from the evaluation procedure. If not, the evaluation procedure will produce information that does not match the manner in which the goals are stated.

More consideration of the uniform information goal in the future will necessitate the incorporation of statistics into regulatory monitoring to a larger extent than in the past. In general, any attempt to gain more information, as well as more uniform information, will require the use of statistics to a much larger extent. Too often in the past, regulatory water-quality monitoring has not been viewed as a statistical sampling program. It is a statistical sampling effort and should be treated as such.

MONITORING SYSTEM EVALUATION

The evaluation of sampling frequencies is only one aspect of monitoring network design which is, in turn, only one aspect of a total monitoring system. Thus, the subject of this report covers a very small part of the total system.

Evaluating sampling frequencies and ensuring that they are reflective of agency policy and management goals can not imply that the total system is meeting management and policy goals.

For example, if the data are not properly handled, analyzed and utilized, then the data may not reach the decision-making levels of the management agency. Thus, any attempt to evaluate sampling frequencies should be accompanied by evaluations of: (1) the other aspects of network design, (2) sample collection procedures, (3) laboratory analyses, (4) data handling operations, (5) data analysis techniques and (6) information utilization procedures.

Unfortunately, there are few evaluation procedures available to assist in the evaluation of the monitoring system or its parts. As more emphasis is placed upon the need for well defined and operated routine monitoring systems for regulatory water-quality management, hopefully the needed evaluation guidelines will be developed.

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APPENDIX A

FØRTRAN Program Used for Analysis of Minnesota Network

```
C   TITLE=TITLE FOR THE EVALUATION BEING DONE THIS RUN
C   ANALY=TYPE OF ANALYSIS BEING DONE THIS RUN - FOR PRINTING PURPOSES ONLY
C   NS=NUMBER OF STATIONS IN THE NETWORK
C   NP=NUMBER OF PARAMETERS INCLUDED IN THE EVALUATION
C   P1,P2,P3,P4=LIMITS ON THE PARAMETER STANDARD DEVIATIONS
C   STA(IS)=DESCRIPTION OF STATION IS
C   PDESC(IP)=DESCRIPTION OF PARAMETER IP
C   OF(IS,IP)=NUMBER OF SAMPLES ALLOCATED TO STATION IS FOR THE IP PARAMETER
C             FOR THE PAST THREE YEARS
C   VP(IS,IP)=VARIANCE OF PARAMETER IP AT STATION IS
C   IYB(IS)=BEGINNING YEAR OF RECORD
C   IYE(IS)=ENDING YEAR OF RECORD
C   OFY(IS,IP)=NUMBER OF SAMPLES ALLOCATED, ANNUAL AVERAGE, TO STATION IS FOR
C              IP PARAMETER IN THE PAST
C   AOF(IS)=COMPROMISED OLD FREQUENCY
C   KSOUT=STATIONS BEING EXCLUDED
C   TN=TOTAL NUMBER OF SAMPLES TO BE ALLOCATED
C   AN(IS,IP)=NUMBER OF SAMPLES ALLOCATED TO STATION IS FOR THE IP PARAMETER
C     AN(IS)=COMPROMISED NEW FREQUENCY
C   DFO(IS,IP)=DEGREES OF FREEDOM FOR OLD PRECISION CALCULATION
C   DFN(IS,IP)=DEGREES OF FREEDOM FOR NEW PRECISION CALCULATIONS
C   OP(IS,IP)=OLD PRECISION OF EACH PARAMETER AT EACH STATION
C   EP(IS,IP)=NEW PRECISION OF EACH PARAMETER AT EACH STATION
C   AOP(IP)=OLD PRECISION MEANS
C   AEP(IP)=NEW PRECISION MEANS
C   SDOP(IP)=OLD PRECISION STANDARD DEVIATION
C   SDEP(IP)=NEW PRECISION STANDARD DEVIATION
C   PERI=PERCENT IMPROVEMENT
      DIMENSION SUM(6),STA(200,4),PDESC(4),OF(200,4),VP(200,4)
      DIMENSION AN(200,4),SUMP(200),AV(200),SUMO(200),OFY(200,4)
      DIMENSION AOF(200),OP(200,4),EP(200,4),LINE(133)
      DIMENSION PDESC1(4)
      DIMENSION IYB(200),IYE(200)
      DIMENSION SUMOP(4),SUMEP(4),SUMOPS(4),SUMEPS(4)
      DIMENSION AOP(4),AEP(4),SDOP(4),SDEP(4)
      DIMENSION KSOUT(40),TITLE(20)
      DIMENSION DFO(200,4),DFN(200)
      DIMENSION ANALY(20)
C
C   READ IN INITIAL VALUES
C
      READ(5,229)(TITLE(A),A=1,20)
  229 FORMAT(20A4)
      READ(5,227)(ANALY(A),A=1,20)
  227 FORMAT(20A4)
      READ(5,1) NS,NP
    1 FORMAT(2I5)
      READ(5,226)P1,P2,P3,P4
  226 FORMAT(4F10.8)
C
C   INITIALIZE SUM TO ZERO
C
      DO 2 I=1,NP
    2 SUM(I)=0.0
C
C   CALL STATION AND PARAMETER DESCRIPTIONS
C
      NS=0
```

```
0022          400 READ(8,11) LINE(15)
0023           11 FORMAT(14X,I1)
0024              IF(LINE(15).NE.7) GO TO 400
0025              READ(8,7)(STA(199,K),K=1,8)
0026            7 FORMAT(//,65X,8A4)
0027              READ(8,20) DUMMY
0028           20 FORMAT(/////////,A1)
0029              DO 8 J=1,MP
0030              READ(8,4)PARA,DESC,DESC1,MS,VAR,IB,IE,IEM
0031            4 FORMAT(1X,I5,2A4,30X,I4,9X,F9.0,46X,I2,7X,I2,1X,I2)
0032              WRITE(6,409) PARA,DESC,DESC1,MS,VAR,IB,IE,IEM
0033          409 FORMAT(1X,I5,2A4,30X,I4,9X,F13.3,46X,I2,7X,I2,1X,I2)
0034              IF( J.NE.1) GO TO 401
0035              IF(MS.GT.45) GO TO 400
0036              IF(MS.LT.10) GO TO 400
0037              IF(IE.NE.76) GO TO 400
0038              IF(IEM.LT.11) GO TO 400
0039              MS=MS+1
0040              DO 402 K=1,8
0041          402 STA(MS,K)=STA(199,K)
0042              WRITE(6,410) MS,(STA(MS,K),K=1,8)
0043          410 FORMAT(5X,I2,5X,8A4)
0044          401 IF(MS.NE.1) GO TO 6
0045              PDESC(J)=DESC
0046              PDESC1(J)=DESC1
0047            6 OF(MS,J)=MS
0048              VP(MS,J)=SQRT(VAR)
0049              IYB(MS)=IB
0050              IYE(MS)=IE
0051            8 CONTINUE
0052              IF(MS.LT.80) GO TO 400
0053            9 CONTINUE
                C
                C   WRITE INPUT DATA
                C
0054              WRITE(6,112) (PDESC(K),PDESC1(K),K=1,MP)
0055          112 FORMAT(18X,2A4,22X,2A4,18X,2A4,18X,2A4,18X,2A4)
0056              DO 113 IS=1,MS
0057          113 WRITE(6,114) (IS,IYB(IS),IYE(IS),(OF(IS,K),VP(IS,K),K=1,MP))
0058          114 FORMAT(1X,3I4,8F15.3/)
                C
                C   INITIALIZE SUMD
                C
0059              DO 106 IS=1,MS
0060          106 SUMD(IS)=0.0
                C
                C   DETERMINE PAST SAMPLING FREQUENCIES
                C
0061              PAR=MP
0062              DO 105 IS=1,MS
0063              DO 107 IP=1,MP
0064          107 OFY(IS,IP)=12.
0065          105 AOF(IS)=12.
                C
                C   CHECKING FOR EXTREMELY LARGE DATA VALUES
                C
0066              KOU=0
0067              DO 221 IS=1,MS
```

```
0068              IF(VP(IS,1).GT.P1)GO TO 222
0069              IF(VP(IS,2).GT.P2)GO TO 222
0070              IF(VP(IS,3).GT.P3)GO TO 222
0071              GO TO 221
0072            222 KOU=KOU+1
0073              KSOUT(KOU)=IS
0074              DO 223 IP=1,MP
0075              AOF(IS)=0.0
0076            223 VP(IS,IP)=0.0
0077            221 CONTINUE
0078              SI=MS
                C
                C   SUM STANDARD DEVIATIONS AT ALL STATIONS FOR EACH PARAMETER
                C
0079              DO 101 IP=1,MP
0080              DO 101 IS=1,MS
0081            101 SUM(IP)=SUM(IP)+VP(IS,IP)
                C
                C   COMPUTE NEW SAMPLING FREQUENCIES
                C
0082            231 CONTINUE
0083              READ(5,230) TN
0084            230 FORMAT(F10.0)
0085              IF(TN.LT.0.0) STOP
0086              DO 102 IP=1,MP
0087              DO 102 IS=1,MS
0088            102 AN(IS,IP)=(VP(IS,IP)/SUM(IP))*TN
                C
                C   AVERAGE SAMPLING FREQUENCIES AT EACH STATION
                C
0089              DO 99 IS=1,MS
0090             99 SUMP(IS)=0.0
0091              DO 103 IS=1,MS
0092              DO 104 IP=1,MP
0093            104 SUMP(IS)=SUMP(IS)+AN(IS,IP)
0094            103 AV(IS)=SUMP(IS)/PAR
                C
                C   COMPUTE OLD AND NEW PRECISION OF EACH PARAMETER AT 90% CONFIDENCE LEVEL
                C
0095              DO 108 IS=1,MS
0096              DO 108 IP=1,MP
0097              IF(VP(IS,IP).LT.0.0) VP(IS,IP)=0.0001
0098              IF(AV(IS).LT.0.0001) GO TO 501
0099              OP(IS,IP)=(1.645*VP(IS,IP))/SQRT(OFY(IS,IP))
0100              EP(IS,IP)=(1.645*VP(IS,IP))/SQRT(AV(IS))
0101              GO TO 108
0102            501 OP(IS,IP)=0.0
0103              EP(IS,IP)=0.0
0104            108 CONTINUE
                C
                C   PRINT RESULTS
                C
0105              WRITE(6,205)
0106            205 FORMAT(1H1)
0107              WRITE(6,206)(TITLE(K),K=1,20)
0108            206 FORMAT(30X,20A4/)
0109              WRITE(6,232)(ANALY(K),K=1,20)
0110            232 FORMAT(35X,20A4/)
```

```
0111            WRITE(6,233)TN
0112          233 FORMAT(35X,'TOTAL NUMBER OF SAMPLES CONSIDERED THIS RUN =',F6.0)
0113            WRITE(6,207)IYB(1),IYE(1)
0114          207 FORMAT(/30X,'DATA RECORD USED IN THE EVALUATION IS FROM',I3,' THRO
                 1UGH',I3)
0115            WRITE(6,208)(KSOUT(K),K=1,KOU)
0116          208 FORMAT(/30X,'STATIONS EXCLUDED - ',15I4)
0117            WRITE(6,10)(PDESC(K),PDESC1(K),K=1,MP)
0118           10 FORMAT(///,1X,'STATION',38X,'OLD',4X,'NEW',9X,2A4,13X,2A4,14X,2A4,
                 111X,2A4)
0119            WRITE(6,12)
0120           12 FORMAT(3X,'NO.',8X,'STATION DESCRIPTION',13X,'FREQ',3X,'FREQ',
                 33X,'OLD PREC'
                 1     ,2X,'NEW PREC',3X,'OLD PREC',2X,'NEW PREC',2X,'OLD PREC',2X,
                 2'NEW PREC'/)
0121            DO 109 IS=1,MS
0122            WRITE(6,3)IS, (STA(IS,K),K=1,8),AOF(IS),AV(IS),(OP(IS,IP),
                1 EP(IS,IP),IP=1,MP)
0123            3 FORMAT(1X,I4,4X,8A4,2X,2F7.2,1X,8F10.3/)
0124          109 CONTINUE
              C
              C   COMPUTATION OF MEAN AND STD. DEV. OF PRECISIONS
              C
0125            DO 201 IP=1,MP
0126            SUMOP(IP)=0.0
0127            SUMEP(IP)=0.0
0128            SUMOPS(IP)=0.0
0129          201 SUMEPS(IP)=0.0
0130            DO 200 IP=1,MP
0131            DO 200 IS=1,MS
0132            SUMOP(IP)=SUMOP(IP)+OP(IS,IP)
0133            SUMEP(IP)=SUMEP(IP)+EP(IS,IP)
0134            SUMOPS(IP)=SUMOPS(IP)+OP(IS,IP)**2
0135          200 SUMEPS(IP)=SUMEPS(IP)+EP(IS,IP)**2
0136            DO 202 IP=1,MP
0137            AOP(IP)=SUMOP(IP)/SI
0138            AEP(IP)=SUMEP(IP)/SI
0139            SDOP(IP)=SQRT((SUMOPS(IP)-(1./SI)*SUMOP(IP)**2)/(SI-1.))
0140          202 SDEP(IP)=SQRT((SUMEPS(IP)-(1./SI)*SUMEP(IP)**2)/(SI-1.))
0141            SNSO=0.0
0142            SNSN=0.0
0143            DO 210 IS=1,MS
0144            SNSO=SNSO+AOF(IS)
0145          210 SNSN=SNSN+AV(IS)
0146            WRITE(6,211)SNSO,SNSN
0147          211 FORMAT(/18X,'TOTAL NUMBER OF SAMPLES',1X,2F8.2)
0148            WRITE(6,203)(AOP(IP),AEP(IP),IP=1,MP)
0149          203 FORMAT(/18X,'PRECISION MEANS',25X,8F10.3)
0150            WRITE(6,204)(SDOP(IP),SDEP(IP),IP=1,MP)
0151          204 FORMAT(/18X,'PRECISION STANDARD DEVIATIONS',11X,8F10.3)
0152            SUMAP=0.0
0153            DO 213 IP=1,MP
0154            DP=(AOP(IP)-AEP(IP))/AOP(IP)
0155          213 SUMAP=SUMAP+DP
0156            PERIM=(SUMAP/PAR)*100.
0157            WRITE(6,215)PERIM
0158          215 FORMAT(//18X,'PERCENT IMPROVEMENT OVER PAST POLICY',F8.2)
0159            GO TO 231
                END
```


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